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A review for the applications and integrated approaches of ground-coupled heat pump systems

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ABSTRACT

During the past few decades, a large number of ground-coupled heat pump (GCHP) systems have been widely applied in various buildings around the world due to the attractive advantages of high efficiency and environmental friendliness. However, most buildings in warm-climate or cold-climate areas have unbalanced loads, dominated by either cooling loads or heating loads. Therefore, it is necessary to employ integrated approaches in the design of GCHP systems to decrease the initial cost of the GCHP systems and, at the same time, to improve the system performance. In this paper, the main integrated approaches of GCHP systems were summarized based on the available references and our experience. Then the suggestions were given. For a heating-dominated building, the combination of a GCHP system with a solar thermal system shows great potential for energy conservation and high-efficiency utilization of the GCHP system. With respect to a cooling-dominated building, the simplest approach is to integrate a GCHP system with a cooling tower although there are more available technologies. It is believed that the high inertia heating or cooling distribution systems such as radiant floors, ceilings or walls are more suitable for GCHP systems. It is highly suggested to establish optimal operational control strategies for integrated GCHP systems according to the climatic conditions, building functions and thermal balance of the ground.

Contents

1. Introduction

The global energy consumption in 2020 would be more than twice of the present level according to the current tendency [1]. Such an increasing energy requirement will aggravate energy shortage and environment pollution. About 40% of the annual global energy demand was consumed by buildings; meanwhile more than half of the building energy demand was consumed by air-conditioning systems [2]. Consequently, it is of great importance in the building field to improve the energy efficiency of air-conditioning systems and exploit renewable energy systems, which can minimize the energy expenditure and reduce the carbon emissions.

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Due to availability, economic and environmental issues, it is expected that the geothermal energy will play an important role in the replacement of fossil fuels. The difference in temperature between the outside air and the ground can be utilized as a pre-heating means in winter and pre-cooling in summer by operating a ground heat exchanger. Therefore, shallow geothermal ground source heat pumps have shown the most significant impact on the direct use of geothermal energy [3,4].

Ground source heat pumps have been applied to a variety of systems that use the ground, groundwater, or surface water as a heat source and sink. Included under this general term are ground-coupled (GCHP), groundwater (GWHP), and surface water (SWHP) heat pumps [5].

As for a GCHP system, a heat-exchanger system which is constructed to exploit effectively the heat capacity of the ground is usually an array of buried pipes running along the length of a building, a nearby field or buried vertically into the ground. As a result, GCHP systems have been given more attention because they are more suitable for buildings with limited space and those in cities with high building density.

The technology of GCHP relies on the fact that, at a sufficient depth, the ground temperature is always higher than that of the outside air in winter and is lower in summer. A GCHP can be used to extract heat from the relatively warm ground and pump it into the conditioned space. In summer, the process may be reversed and the heat pump may extract heat from the conditioned space and send it out to a ground heat exchanger that warms the relatively cool ground [6,7].

In this paper, the applications of GCHP systems in civil buildings were reviewed. And then, different integrated approaches of GCHP systems were summarized based on the available references and our experience. Finally, some suggestions on the design of GCHP systems were presented.

2. Applications of GCHP systems in civil buildings

It was reported that ground source heat pump technology was well established with over 550,000 units installed worldwide and with more than 66,000 units installed annually. About 80% of the units installed worldwide are domestic [7]. The majority of these projects are GCHP systems. GCHP systems have become attractive choices for both residential and commercial buildings because of their higher energy efficiency compared with conventional air-source heat pump (ASHP) systems.

Elisabeth Kjellsson et al. [8] reported that the use of GCHP systems for heating and domestic hot water in dwellings was common in Sweden. Yasuhiro Hamada et al. [9] described a GCHP system using friction piles as heat exchangers for air-conditioning of a building for both office and residential use. Long-term space heating operation measurements indicated that the average coefficient of performance (COP) for space heating was quite high at 3.9, and the seasonal primary energy reduction rate compared with a typical air-conditioning system reached 23.2%.

Michopoulos et al. [10] presented a vertical ground heat exchanger (GHE) of parallel connection coupled to a heat pump system for air conditioning a public building in northern Greece. It was proved that the energy demand of the system was significantly lower, compared to that of conventional heating and cooling systems. The primary energy required by the system for heating was estimated to be lower by 45% and 97% (period average) as compared to that of air-to-water heat pump based and conventional oil boiler, respectively. In cooling mode the relevant differences were estimated at 28% and 55% for air-to-water and air-to-air heat pump based systems.

Hwang et al. [11] presented the cooling performance of a water-to-refrigerant type GCHP system installed in a school building in Korea. The average cooling coefficient of performance and overall COP of the GCHP system were found to be ∼8.3 and ∼5.9 at 65% partial load condition, respectively. While the air source heat pump system, which had the same capacity with the GCHP system, was found to have the average COP of ∼3.9 and overall COP of ∼3.4, implying that the GCHP system was more efficient than the air source heat pump system due to its lower temperature of condenser.

Sanner et al. [12] reviewed the early development of GCHP systems for commercial buildings, and pointed that the utilization of GCHP systems in commercial applications offered some economic and environmental advantages.

Cui et al. [13] reported that a GCHP system could be used to meet the energy requirement of space heating, cooling and hot water supply for an indoor swimming pool. It was concluded that the operation cost of such a system was reduced by 50% compared with a system including a water chiller and an oil boiler.

The application of GCHP systems in civil buildings were also reported by Hochstein et al. [14], Gao et al. [15], O'Sullivan et al. [16], Serpen et al. [17] and Thain et al. [18]. It is concluded that GCHP projects contain various categories, such as office building, hotel, residential building, workshop building, school, villa house, hospital and emporium. They have shown great potential in the energy conservation of air-conditioning systems in civil buildings.

3. Integrated approaches of GCHP systems

It is well known that GCHP systems can achieve better energy performance in specific locations where heating and cooling loads of buildings are well balanced all year round because of the long-term transient heat transfer in the ground heat exchangers. Man et al. [2] reported that, when installed in moderate-climate regions, the COP of the GCHP systems was between 3 and 4, which was 20–30% higher than that of the conventional ASHP systems [2].

However, most buildings in warm-climate or cold-climate areas have unbalanced loads, dominated by either cooling loads or heating loads. When GCHP systems are used in the cooling-dominated buildings in warm climates, more heat will be rejected to the ground than that extracted from the ground on an annual basis. The heat buildup within the ground will definitely increase the ground temperature, which can consequently deteriorate the system performance over time. Similarly, when GCHP systems are applied to heating-dominated buildings in cold climates, the heat extracted from the soil by the heat pump in winter is much larger than that injected into the soil in summer. In such two cases, the utilizations of GCHP systems for cooling or heating often require a larger ground heat exchanger, which may be restricted by the construction sites and the initial cost [19].

An alternative to decrease the initial cost of the GCHP system and, at the same time, to improve the system performance is to employ integrated approaches in the design of GCHP systems.

3.1. GCHP systems integrated with solar energy

GCHP systems, in combination with solar heat, have been tested with different system designs during the last 25 years in several countries. In such systems, the solar collectors may supply heat directly to the domestic hot water systems, the building heat distribution systems, increasing the temperature of the evaporators in the heat pumps, recharging the boreholes or combinations of all.

Bi et al. [20] carried out the theoretical and experimental studies of a solar-assisted GCHP system. The heating mode of the system could be alternated between a solar energy-source heat-pump and

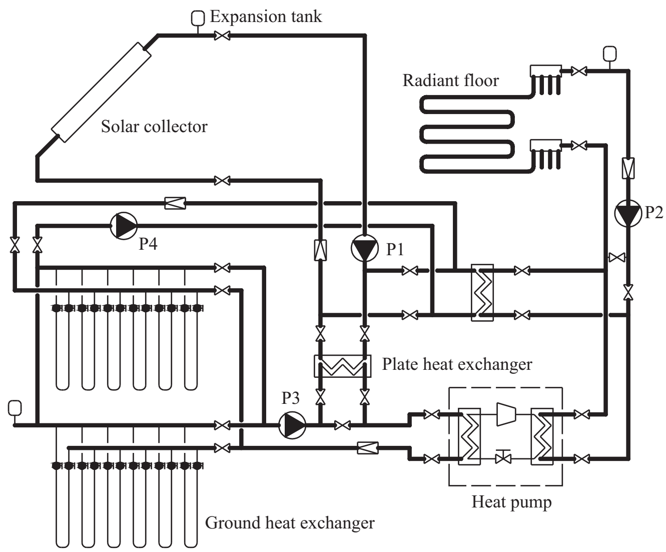

Fig. 1. Flow diagram of the solar-assisted GCHP system.

a GCHP. The experimental results were as follows: for the solar energy-source heat-pump system, the average heating load was 2334 W and the average COP was 2.73; for the GCHP system, the corresponding performance was 2298 W and 2.83, respectively; and for the solar-assisted GCHP system, the corresponding performance was 2316 W and 2.78, respectively. The experimental results showed the feasibility of the application of a solar-assisted GCHP system.

Wang et al. [21] presented the experimental study of a solar-assisted GCHP system with solar seasonal thermal storage installed in a detached house in Harbin (126°46′E, 45°45′N). Fig. 1 shows the flow diagram of the solar-assisted GCHP system. The system operated in three modes throughout the year and each mode was controlled automatically. In mode 1, the solar collection system and the underground heat exchange system worked, and the solar collectors injected heat into the soil through the GHE. In mode 2, half of the GHE cooled the building directly using the soil as the heat sink, and the other half went on working the same as mode 1. In mode 3, solar collectors and the GCHP heated the building alternately.

The solar seasonal thermal storage was conducted throughout the non-heating seasons. In summer, the soil was used as the heat sink to cool the building directly. In winter, the solar energy was used as a priority, and the building was heated by the GCHP system and solar collectors alternately. The experimental results showed that the system could meet the heating and cooling energy needs of the building. In the heating mode, the heat directly supplied by solar collectors accounted for 49.7% of the total heating output, and the average COP of the heat pump and the system were 4.29 and 6.55, respectively. In the cooling mode, the COP of the system reached 21.35, as the heat pump was not necessary to be started. After one year of operation, the heat extracted from the soil by the heat pump accounted for 75.5% of the heat stored by solar seasonal thermal storage. The excess heat raised the soil temperature to a higher level, which was favorable for increasing the COP of the heat pump. It was said that the design as well as the operation mode of this system was reasonable for severe cold areas.

Based upon a single family dwelling, Elisabeth Kjellsson et al. [8] analyzed different systems with combinations of solar collectors and GCHP systems. According to the simulation, large differences were found between different system alternatives. The optimal design was when solar heat was used to produce domestic hot water during summertime and recharge the boreholes during wintertime. The advantage was related to the rate of heat extraction from the boreholes as well as the overall design of the system. Another advantage with solar heat in combination with GCHP systems was when the boreholes or neighboring installations were drilled so close that they thermally influence each other.

The drawback was that the complexity in these solar-assisted GCHP systems might cause difficulties in realizing optimal system design and operational control [8].

3.2. GCHP systems integrated with cooling towers

When the GCHP technology is used in warm or hot-weather areas, the heat rejected into the ground by the GCHP systems will accumulate around the ground heat exchangers. This heat accumulation will result in degradation of system performance and increment of system operating costs. This problem can be resolved using cooling towers as the supplemental heat rejecters to reject the accumulated heat. Fig. 2 shows the flow diagram of the GCHP system integrated with a cooling tower [2].

Man et al. [2] suggested to choose the capacity of the cooling tower according to the difference between peak value and average value of the annual hourly cooling loads and to activate the cooling tower when the wet-bulb temperature of ambient air was low. The simulation results indicated that, this integrated approach was suitable for hot-weather areas like Hong Kong. The economic advantage of the GCHP system integrated with a cooling tower was very obvious, especially after long term running. Compared with the traditional GCHP system, 34.32% initial costs saving, 22.85% operating costs saving in the first year running and 53.59% operating costs saving in ten years' running could be achieved using the integrated approach for a sample building.

Zhang [22] proposed to choose the total length of the GHE according to the value of the heat absorption capacity in winter when the GCHP systems were applied in cooling-dominated buildings. The cooling towers could be used to remove the peak cooling loads in summer. Based on a building with the cooling load and heating load of 1900 kW and 1300 kW, respectively, five different systems were compared, as shown in Table 1. The payback time of the GCHP system integrated with a cooling tower was 5 years compared with the air-source heat pump system.

3.3. GCHP systems integrated with thermal storage technologies

Solar energy can be used to realize seasonal heat storage for GCHP systems during the non-heating seasons, which has been reported in Section 3.1 [21]. With regard to cold storage, Wei et al. [23] proposed an integrated approach combining a GCHP system with an ice storage system, which was constructed in a building with the covered area of 184,000 m^2. The heat pump was capable of being operated in three different modes, which were (a) heating mode; (b) ice storage mode; and (c) cooling mode. In summer, the GCHP system was used to realize the ice storage operating mode during the off-peak period, which was then utilized for cooling in the daytime. The GCHP system was turned on and worked together with the ice storage tank during the peak cooling load period. In winter, the GCHP system supplied heating for the whole building. Fig. 3 shows the flow diagram of the GCHP system integrated with an ice storage system. Compared with a conventional heating and air-conditioning system, the operating cost of this system could be reduced by 42.7–71.4% in summer, correspondingly, 50% in winter.

In some GCHP systems, thermal storage was implemented only by means of the ground heat exchangers instead of auxiliary thermal storage devices.

Gasparella et al. [24] pointed that, based on the reasonable system design and operation modes, the thermal recharge of the ground could be performed in summer while satisfying the cool-

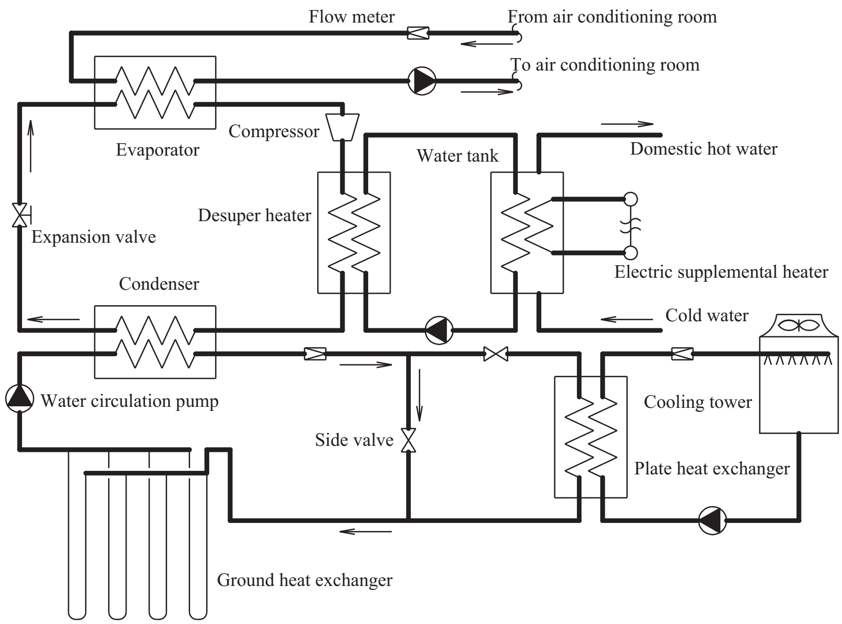

Fig. 2. Flow diagram of the GCHP system integrated with a cooling tower.

Table 1
Comparison of five different systems.

Items compared	GCHP system integrated with a cooling tower	Water chiller + gas boiler	Air-source heat pump system	Water chiller + air-source heat pump	Gas powered LiBr absorption chiller
Initial cost (RMB)	6,910,000	4,280,000	4,680,000	4,450,000	5,030,000
Operation and maintenance cost (RMB)	460,000	780,000	910,000	850,000	800,000
Payback period (year)	–	8.2	5	6.3	5.5

ing needs directly through the ground heat exchanger. In winter the GCHP system benefited from the higher temperature level at which the underground thermal energy storage was operated.

Fan et al. [25] presented the configuration of a vertical dual functional geothermal heat exchanger used in an integrated soil cold storage and GCHP system. By means of a suitable operation mode, the system charged cold energy to the soil at night and produced chilled water at daytime in summer, and supplied hot water for heating in winter. The simulation results indicated that the system transferred 71.51% of the original power consumption at daytime to that at nighttime for the demonstration building. And the net energy exchange in the soil after one-year operation was only 2.28% of the total cold energy charged. Such a new system and new operation mode was testified to be effective to solve the imbalance between summer cooling load and winter heating load. Besides, the use of the lower cost power during the off-peak period can decrease the power consumption in peak period.

In addition, some novel thermal storage measures have been reported. Hüseyin Benli et al. [26] developed a ground-source heat pump system integrated with a phase change material latent heat storage system to use natural energy, to the extent possible, for thermal environment control of the greenhouse. Based upon the measurements made in the heating mode from 1 September 2005 till 30 April 2006 in Elazig, Turkey, the average heating COP of the ground-source heat pump unit and the overall system COP were obtained to be in the range of 2.3–3.8 and 2–3.5, respectively. These results showed that the utilization of such a system was a suitable approach for greenhouse heating in this district.

Gan et al. [27] described an experimental and computational investigation into a ground-source heat pump system that utilized rainwater as a heat source/sink by employing a heat exchanger integrated into a water storage tank and surrounding soil. It was reported that the deployment of the system would reduce the need for heating/cooling of buildings as well as mains water supply and so reduce energy costs and CO_2 emissions.

3.4. GSHP systems integrated with conventional air-conditioning systems

A possible way to improve the efficiency of GCHP systems can be achieved by combining them with other conventional HVAC systems. A proper management of the combined system could potentially produce a system performance better than the performance achieved by each one working independently [28].

Pardo et al. [28] presented an integrated GCHP system and compared the electrical energy consumption and the energy efficiency with those of other five different air conditioning layouts (i) air to water heat pump; (ii) GCHP; (iii) GCHP + air to water heat pump; (iv) air to water heat pump + thermal storage device; (v) GCHP + thermal storage device for a cooling dominated office building in the Mediterranean coast. The presented integrated configuration comprised a GCHP, an air to water heat pump and a thermal storage device. The GCHP was used to store thermal energy during the night. The procedure to supply thermal energy to the load in cooling mode was as follows. The energy stored during the night in the storage device was used to satisfy the thermal demand. If the thermal storage device had not enough capacity, the GCHP was switched on to support it. If these two elements were still not enough, the air to water heat pump was switched on. Finally, the thermal storage device was by-passed when its outlet water temperature was higher than its inlet water temperature and only the

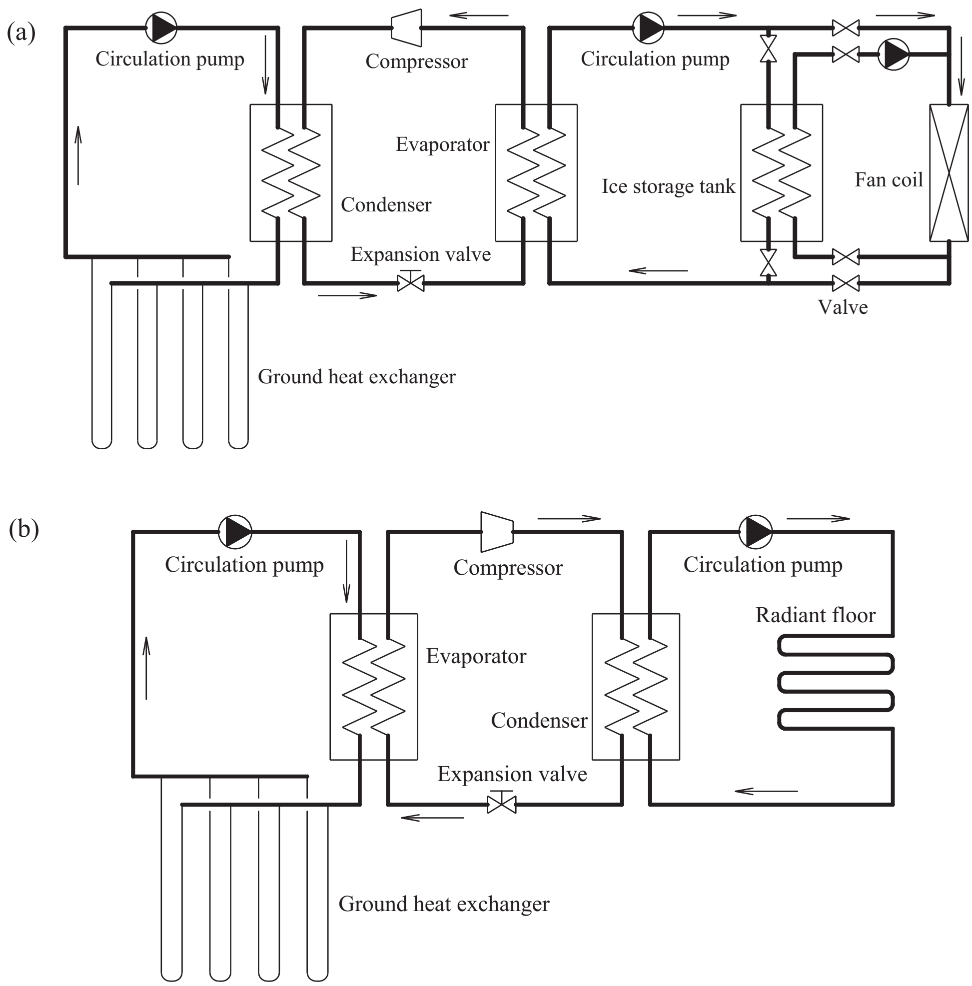

Fig. 3. Flow diagram of the GCHP system integrated with an ice storage system. Operating modes in (a) summer and (b) winter.

GCHP and the air to water heat pump supplied thermal energy to the load.

It was shown that the electrical energy consumption obtained when the presented system employed a suitable configuration was of around 60% compared with an HVAC system driven by an air to water heat pump and around 82% compared with an HVAC system driven by a GCHP. Furthermore, the economic cost assessment showed that this configuration had the best pay-back period and long term cost efficiency.

Jeon et al. [29] studied the performance of an integrated cooling system that combined a screw water chiller with a GCHP, as was shown in Fig. 4. It was seen that the COP of the GCHP was lower than that of a conventional chiller in the monitored building. However, the integrated cooling system helped to stably provide the required cooling capacity at high-load conditions. The integrated cooling system was simulated by varying four operating parameters: the operating schedule, chilled water temperature, dry-bulb temperature, and entering water temperature. The chilled water temperature was ascertained as being the most effective control parameter in the integrated cooling system. With proper control of the chilled water temperature, a building could lower power consumption by 13% while maintaining thermal comfort.

3.5. GSHP systems integrated with dehumidification systems

Gasparella et al. [24] proposed an integrated approach of an underground thermal energy storage (UTES) system with a desiccant based air handling unit (AHU). Different from the conventional solutions, the humidity control in summer was obtained by chemical dehumidification of the ventilation airstream, so the integrated system could operate in a free-cooling mode with the borehole heat exchangers water temperature generally suitable to meet the sensible load without any integration with the chillers. In winter the main benefits were due to the higher temperature level at which the UTES works and to the AHU configuration allowing sensible and latent heat recovery. For the same reasons, the required UTES size was sensibly smaller, reducing in this way not only the operation but also the investment cost.

The proposed system had been analyzed by a computer simulation referring to a modern office building in the climate of northern Italy. In this case, the integrated system saved around 30% of primary energy per year with respect to a conventional HVAC system with gas fired water heaters for heating and electric compression chillers for cooling.

Chen et al. [30] reported another similar GCHP system with the rated cooling capacity of 14 kW in Shanghai Institute of Building Science. Fig. 5 shows the flow diagram of the GCHP system integrated with a dehumidification system. In summer, a fresh air handling unit with sensible and latent heat recovery was installed for the humidity control. The chilled water with the temperature of 18 °C was delivered into the radiant panels in the building, which was necessary to deal with sensible cooling load. If the water temperature from the GHE was lower than 16 °C, the water would be circulated between the GHE and the radiant panels by means of a

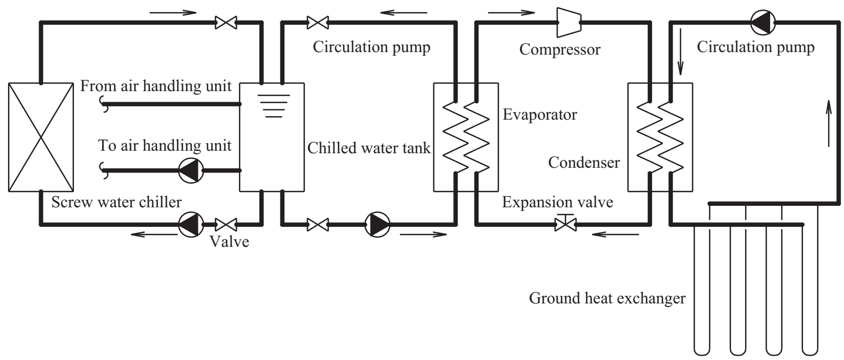

Fig. 4. Flow diagram of the GCHP system integrated with a screw water chiller.

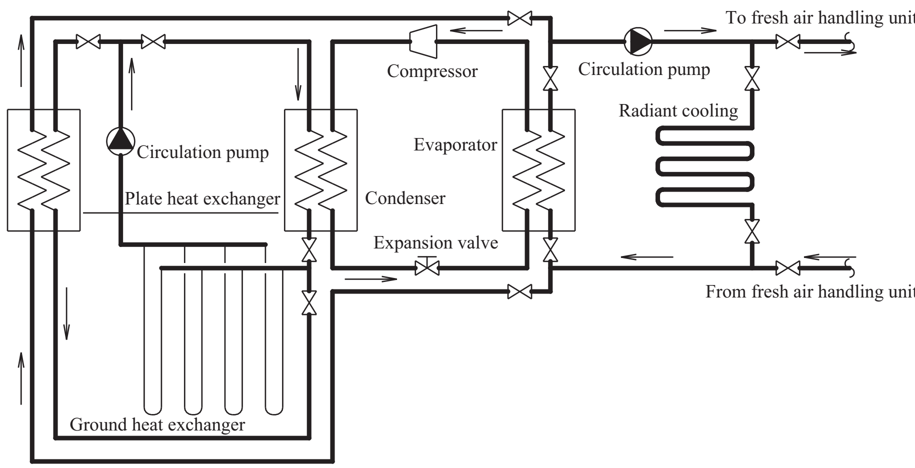

Fig. 5. Flow diagram of the GCHP system integrated with a dehumidification system.

Table 2
Operating parameters of the GCHP system in Shanghai Institute of Building Science.

Season	Water temperature between GCHP and radiant panels (°C)	Water temperature between GCHP and GHE (°C)	Surface temperature of radiant panels (°C)	Indoor air temperature (°C)	Indoor air relative humidity (%)
Summer	18/21	30/25	20–22	24–26	≤55
Winter	32/28	10/15	26–28	22–24	–

plate heat exchanger. Otherwise, the GCHP worked to supply cooling for the building. The chilled water was also delivered into the fresh air handling unit to precool the fresh air, which was meaningful for the energy conservation of electric dehumidifier in the fresh air handling unit. The operating parameters were shown in Table 2. The average COP of the system was 4.2 according to the experimental results. It was also reported that the unit area annual mean operating cost was 12.3 RMB/m^2 [31].

3.6. *GCHP systems integrated with heat recovery technologies for constant temperature and relative humidity air-conditioning systems based upon our experience*

A constant temperature and relative humidity air-conditioning system driven by ground source heat pumps was developed for Minhang archives building of Shanghai. The system mainly consists of two heat pumps with the rated cooling capacity of 500 kW for each, 280 boreholes with 80 m in depth, air handling units and circulating pumps. All the components were connected by tubes and valves to form the whole circulating system. The flow diagram of the system was shown in Fig. 6. Based on the thermal characteristics and orientations of the rooms, four water loops were installed: (i) eastern AHUs for the archives houses in the east; (ii) western AHUs for the archives houses in the west; (iii) offices fan-coil for the office rooms; (iv) corridors fan-coil for the corridors. Through valves located on the pipes, the GCHP system can be switched to different operating modes according to different seasons.

In the cooling mode, the valves 1, 3, 9 and 11 which are depicted in Fig. 6 are closed; however, the valves 2, 4, 5, 6, 7, 8, 10, 12, 13, 14, 15 and 16 are opened. The valves attached to the chilled water splitter and collector, which are 17, 18, 19, 20, 21, 22, 23 and 24, are opened. Thus, the evaporators of the heat pumps supply chilled water to the AHUs and the fan coil units. Meanwhile, the valves 25, 26, 29 and 30 are also opened for the purpose of reheating the air in AHUs. In order to improve the soil energy balance, the technology of heat recovery that part of the heat extraction from the condenser was delivered to reheat the air in AHUs was used in the cooling mode. As a result, the water from the condensers is divided into two portions: part of it flows into the ground heat exchanger while the rest into the heating coils in the AHUs. The air is at a very low temperature after the cooling coils because the cooling coils are used to dehumidify the air. Consequently, in order to achieve the constant temperature and relative humidity, the air need to

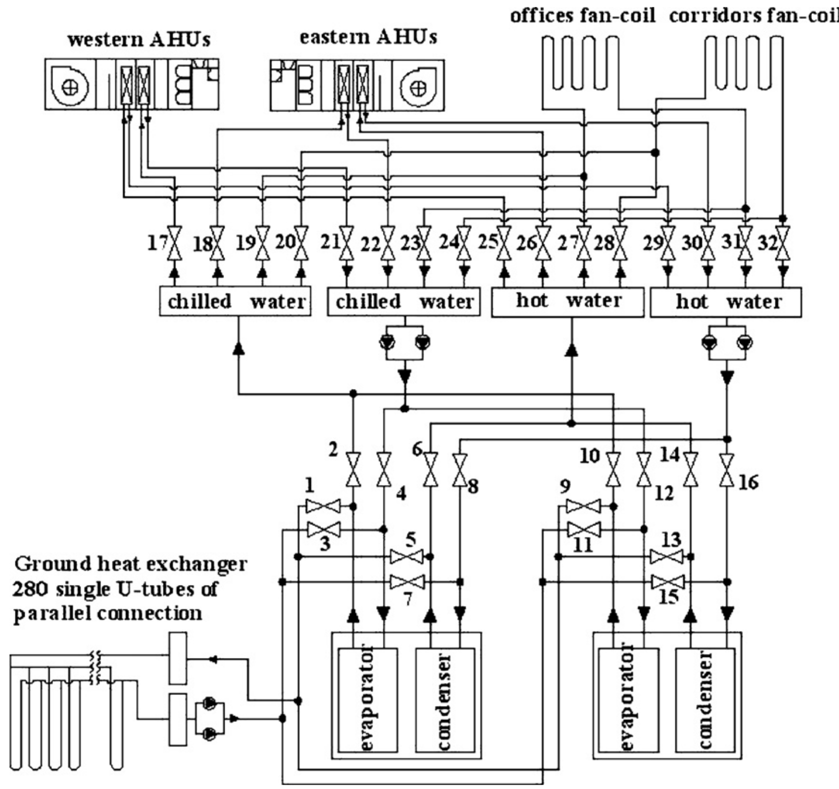

Fig. 6. Flow diagram of the GCHP system.

be reheated by the heating coils before it is sent into the archives houses.

In the heating mode, one heat pump is operated in heating mode while the other is in cooling mode. With respect to the one in heating mode, the valves 2, 4, 5 and 7 which are depicted in Fig. 6 are closed; whereas, the valves 1, 3, 6 and 8 are opened. The valves attached to the hot water splitter and collector, which are 25–32, are also opened. Thus, the condenser of the heat pump in heating mode supplies hot water to the AHUs and the fan coil units. As for the other heat pump in cooling mode, the valves 9, 11, 14 and 16 are closed, while the valves 10, 12, 13 and 15 are opened. Meanwhile, the valves 17, 18, 21 and 22 are also opened for the purpose of dehumidifying the air in AHUs. When the air in the AHUs needs to be dehumidified, the evaporator of the heat pump in cooling mode supplies chilled water to the AHUs to dehumidify the air.

Based on all-the-year-round experimental data, it was concluded that under the weather condition of Shanghai, the GCHP system could be used to satisfy the constant temperature and relative humidity air-conditioning for the archives building. The average COP of the heat pump under the typical summer weather condition of Shanghai was 5.4. Meanwhile, it was 5.2 for the typical winter weather condition. All-the-year-round experimental data showed that the average COP of the heat pump in summer was 4.7, correspondingly, 4.6 in winter and 3.9 in transition seasons. The heat recovery in the cooling mode that part of the heat extraction from the condenser was used to reheat the air in AHUs could reduce the heat rejected to the soil by 33.3%, which was helpful to the balance of the earth energy. Compared with an air source heat pump system which is widely used in archives buildings, the operating cost of the GCHP system was reduced by 55.8% and the payback time would be two years.

4. Conclusions and suggestions

During the past few decades, a large number of GCHP systems have been widely applied in various buildings around the world due to the attractive advantages of high efficiency and environmental friendliness.

A novel application of GCHP systems was for constant temperature and relative humidity air-conditioning systems. There are some buildings, for example the archives, which require constant indoor temperature and humidity all the time. The GCHP system has been testified to be applicable to the air-conditioning systems of such buildings by means of heat recovery technology.

In order to improve the efficiency of GCHP systems as well as reduce the initial cost of boreholes, integrated approaches are highly suggested to be adopted in the design of GCHP systems. The main integrated approaches and their applications according to building loads were summarized in Table 3. For a heating-dominated building, the combination of a GCHP system with a solar thermal system shows great potential for energy conservation and high-efficiency utilization of the GCHP system. With respect to a cooling-dominated building, the simplest approach is to integrate a GCHP system with a cooling tower although there are more available technologies.

Generally speaking, the GCHP systems with reasonable integrated approaches were able to be efficiently operated with the COP of 3–5. In addition, they showed great potential to yield a payback of about 2–5 years compared with the conventional air-conditioning systems.

As for residential buildings and the public buildings with the requirement of hot water supply, especially for those in warm-climate areas, the GCHP systems are suggested to be integrated with heat recovery devices to make use of heat rejection from con-

Table 3
Main integrated approaches of GCHP systems.

Integrated approaches	Heating-dominated buildings	Cooling-dominated buildings
Integrated with solar energy	√	
Integrated with cooling towers		√
Integrated with thermal storage technologies	√ (Heat storage)	√ (Cold storage)
Integrated with conventional air-conditioning systems	√	√
Integrated with dehumidification systems		√
Integrated with heat recovery technologies		√

densers. Therefore, they are capable of supplying hot water besides heating and cooling. Such an integrated approach is also helpful to the balance of the earth energy.

With regard to terminal equipments of GCHP systems, it is believed that the high inertia heating or cooling distribution systems like radiant floors, ceilings or walls are more suitable for GCHP systems. In winter, the required temperature of floor heating is generally below 60 °C which is suitable for GCHP systems. In summer, compared with fan coil cooling systems, radiant cooling systems require a higher chilled water temperature of about 18–20 °C. This means that the evaporating temperature of the heat pumps rises about 10 °C, which leads to the increase of COP of GCHP systems. However, the radiant cooling systems are always needed to be assisted by independent dehumidification AHUs for the humidity control. Another benefit of radiant floors, ceilings or walls is their capability to regularize the heating or cooling load imposed on the GCHP systems.

Anyway, the integrated GCHP systems may be more complicated than the ordinary GCHP systems. Consequently, it is highly suggested to establish optimal operational control strategy according to the climatic conditions, building functions and thermal balance of the ground.

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